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NPS Acquisition Research Program  
Attn: James B. Greene, RADM, USN, (Ret.)  
Acquisition Chair  
Graduate School of Business and Public Policy  
Naval Postgraduate School  
555 Dyer Road, Room 332  
Monterey, CA 93943-5103  
Tel: (831) 656-2092  
Fax: (831) 656-2253  
E-mail: [jbgreene@nps.edu](mailto:jbgreene@nps.edu)

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# A Three Stage Multi-attribute Procurement Auction: A Proposal for Department of Defense (DoD) Vendor Selection Decisions

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**Francois Melese**—Dr. Melese joined NPS in 1982. Today he is Professor of Economics at the Defense Resources Management Institute (DRMI). In 2008, he helped edit the DoD's first Strategic Management Plan. Professor Melese has published over 50 articles and book chapters on a variety of topics and together with NPS colleagues was among the first to apply transaction cost economics to generate new insights into military cost estimating, and the make-or-buy decision. In 2009, NATO HQ asked Dr. Melese to organize a major NATO meeting to celebrate the 60<sup>th</sup> anniversary of the Alliance: "Building Integrity and Defense Institution Building."

Francois Melese  
Defense Resources Management Institute (DRMI)  
School of International Graduate Studies (SIGS)  
Naval Postgraduate School  
Code 64, NPS  
699 Dyer Rd.  
Monterey, CA 93943  
fmelese@nps.edu  
Office: 831-656-2009

**Jay Simon**—Dr. Simon is an Assistant Professor of Decision Science at the Defense Resources Management Institute (DRMI). His main research focus is multi-attribute preference modeling. His current and recent work includes a prostate cancer decision model, preference models for health decisions, preferences over geographic outcomes, altruistic utility modeling, and time discounting anomalies. He is a member of the Institute for Operations Research and the Management Sciences (INFORMS), and the Decision Analysis Society of INFORMS. Dr. Simon joined the DRMI faculty in August 2009.

Jay Simon  
Defense Resources Management Institute (DRMI)  
School of International Graduate Studies (SIGS)  
Naval Postgraduate School  
Code 64, NPS  
699 Dyer Rd.  
Monterey, CA 93943  
jrsimon@nps.edu  
Office: 831-656-2457  
Home: 831-920-1454

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## Abstract

This paper explores vendor selection decisions where competing vendors offer similar products with multiple non-price attributes. Traditional "multi-attribute auctions" such as the USAF Air Tanker competition include prices alongside other attributes in vendor proposals. Buyers generally select winning bidders using a weighted average of price and non-price attributes. A different approach is recommended here: to embed vendor prices directly in the buyer's budget constraint. A first step is to conduct a simple multi-attribute auction with a fixed budget. The government buyer only evaluates vendor proposals that satisfy the budget constraint, choosing the proposal (non-price attribute bundle) which offers the greatest "value for money" (i.e., budget). The next step is to address budget uncertainty, expanding the model to incorporate a range of budgets. This leads to several interesting



results, including that the traditional practice, and classroom technique, of eliminating dominated alternatives can lead to sub-optimal decisions. Improving public procurement decisions requires forecasting a range of future budgets, and soliciting information from vendors that allows procurement alternatives to be defined as functions of the value offered by each vendor over a range of budgets, rather than as a single point in budget-value (cost-effectiveness) space. Under more realistic budget scenarios, different vendor selection decisions will occur that benefit both troops and taxpayers.

## Background and Introduction

This paper offers a model to guide public procurement decisions in severely constrained budget environments. The global financial crisis swiftly evolved into a debt crisis that increasingly constrains government spending. The US is not immune. The federal debt, at roughly 80% of GDP and rising, is set to seriously constrain discretionary federal spending. Today, mandatory expenditures on Medicare, Medicaid, Social Security, Interest on the Debt, etc., make up over 60% of the federal budget, and continue to grow. By far the largest component of the corresponding, and shrinking, discretionary budget (more than half) is spent on national defense. The challenge then, is to develop an approach to accommodate the future budget uncertainties that will increasingly face federal agencies, and in particular, the US Department of Defense (DoD).

This paper explores vendor selection decisions where competing vendors offer similar products (computers, logistics packages, weapon systems, etc.) that incorporate multiple non-price attributes. In most multi-attribute auctions, vendor prices are included alongside other attributes as part of the vendor's proposal. Along with political considerations, a weighted average of price and non-price attributes is generally used by governments to help select the winning bidder. The approach recommended here is different. In the spirit of "Cost as an Independent Variable" (CAIV), the proposal is to incorporate vendor prices in the buyer's budget constraint.

A first step is to conduct a simple multi-attribute auction with a fixed budget (point estimate) for the program (product or service). In this case, the government buyer chooses from a set of vendors that each submit their best offers—non-price attribute bundles that fall within the specified budget. The next step is to address the political realities of budget uncertainty. This requires an expansion of the model that incorporates a range of possible budgets (e.g., optimistic, pessimistic, and most likely). This leads to several interesting results. Perhaps the most surprising is that the traditional practice, and classroom technique, of eliminating dominated alternatives can easily lead to sub-optimal decisions.

Finally, the model is generalized to capture budget uncertainty through the specification of a probability distribution (density function) over the range of possible budgets. The dual fundamental insights of this paper are that public procurement decisions can be improved if: i) interval estimates (ranges) of future budgets (and corresponding probability distributions) are forecasted, and ii) information from vendors is solicited that allows procurement alternatives to be defined as a function of value (non-price attributes) over a range of possible budgets, rather than as a single point in budget-value (cost-effectiveness) space.

Over the next five years, the US Department of Defense (DoD) plans to spend more than \$357 billion on the development and procurement of major defense acquisition programs (MDAPs). According to the Government Accountability Office (GAO, 2009), the DoD's goal is to "achieve a balanced mix of weapon systems that are *affordable*" [emphasis added]. With this goal in mind, a multi-attribute first price, sealed bid procurement auction is



proposed that extends traditional price-only auctions to one in which competition takes place exclusively over specific bundles of desired non-price attributes or characteristics.

In this model, prices/costs do not appear in the buyer's value function. Instead, in the spirit of "cost as an independent variable" (CAIV), prices/costs are incorporated in the buyer's affordability constraint. Larsen (2007) provides the following explanation of CAIV:

All acquisition programs/issues consist of three fundamental elements: cost, performance and schedule. Under CAIV, performance and schedule are considered a function of cost. Cost and affordability should be a driving force not an output after potential solutions are established.

Michael and Becker (1973) and others also discuss the importance of separating prices from multi-attribute measures of value. This is especially important for agencies that face budget uncertainty.

For example, given the growing pressure on defense budgets from expanding federal deficits, the military's "bow wave" of planned procurement contracts and operating cost commitments is not affordable, and has recently threatened several MDAPs. [e.g., the Army's Future Combat System (FCS) and the Air Force Joint Strike Fighter (JSF) program] An important lesson is that different optimal vendor selections likely would have taken place under more realistic budget scenarios, and that this would have benefited both troops and taxpayers.

This paper explores vendor "performance competition" under alternative budget scenarios. Given a target budget for the program (e.g., computers, vehicles, weapons, logistics packages, etc.), competing vendors generate multi-attribute (performance) offers based on their individual costs, technology, productivity, production processes, supply chains, etc. Each vendor (seller/bidder) is provided the same budget authority guidance from the procurement agency's projected funding forecast (a point estimate). Vendors respond by offering their best possible non-price attribute bundles.

In the model, a vendor's proposal (offer) depends on the buyer's budget, and the individual vendor's costs of supplying each attribute along with the production technology they have available to combine those attributes. Competition between vendors takes place exclusively over product performance (collections of non-price attributes) for a given budget. The government buyer's value function facilitates the evaluation vendor proposals (bundles of non-price attributes) and the selection of a winner.<sup>1</sup>

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<sup>1</sup> Consider a simple example. Suppose a dozen impact resistant notebook computers are required for a provincial reconstruction team (PRT) heading to Afghanistan. The team believes the most likely budget available for these computers will be \$20,000, and it reveals this to the competing vendors. For this particular budget, each vendor offers a different combination of components, attributes and quality characteristics based on its technology, its capital and labor productivity, and the fixed and variable costs embedded in its supply chains. Given the different sets of a dozen computers offered by the each vendor, the team then selects the vendor that offers the best value (mix of attributes) for their budget, or the one that maximizes their private value function. With the funding uncertainty inherent in defense programs, this paper suggests that vendors be asked to provide offers for more than one budget level (say an optimistic budget of \$25,000 and a pessimistic budget of only \$15,000). In general, the recommendation is that each competing vendor's proposal be re-defined as a function of the bundle of multiple (non-price) attributes they can offer over the range of possible budget levels (e.g., optimistic, pessimistic, and most likely).



A straightforward extension is to allow the buyer to offer a range of possible budgets. However, this involves a more complex solicitation, inviting proposals from different vendors for each possible budget. The significant benefit is that it provides a more robust view of a vendor's ability to provide performance. The "expansion path" generated for each vendor shows how that vendor's proposal changes as the budget increases or decreases.

This approach can be thought of as a strategic choice of auction mechanism for a buyer when possible overall budget authorities for the program can only be estimated/forecasted, and the products/services are highly differentiated and complex. It combines the competitive advantages of auctions with the flexibility of a decision based on multiple attributes of the product.

In our formulation, both seller and buyer suffer from imperfect and asymmetric information. The seller does not know the relative weights the buyer assigns to the attributes. Meanwhile, the buyer does not know the sellers' costs of producing a particular attribute, nor the technology (production functions) that combines those attributes into the desired products. Parkes and Kalagnanam (2005) explain this asymmetry in the case of a seller's private information: "[S]eller costs can be expected to depend on [the] local manufacturing base and sellers can be expected to be well informed about the cost of (upstream) raw materials."

Loerch, Koury, and Maxwell (1999) discuss a "Value Added Analysis" approach that is similar to ours in employing multi-attribute preferences in weapon systems acquisition decisions. Our approach differs from theirs in that we incorporate the vendors' decision-making explicitly into the model, and capture the issue of asymmetric information.

Blondal (2005) discusses a two-stage<sup>2</sup> bidding process similar to ours, in which the procuring agency issues a general request, and then later issues a more detailed request based on the responses received. The US Federal Acquisition Regulations (2005) provide guidance in subpart 14.5 on another two-step process for government agencies:

Step one consists of the request for, submission, evaluation, and (if necessary) discussion of a technical proposal. No pricing is involved. Step two involves the submission of sealed price bids by those who submitted acceptable technical proposals in step one. Invitations for bids shall be issued only to those offerors submitting acceptable technical proposals in step one. An objective is to permit the development of a sufficiently descriptive and not unduly restrictive statement of the Government's requirements especially useful for complex items.

The approach proposed in this paper is similar, but differs from this two-step bidding process in that the competition is over non-price attributes, and the price is captured in the budget authority (or affordability) constraint.

Much of the multi-attribute auction literature (Che, 1993; Beil & Wein, 2003; and Parkes & Kalagnanam, 2005; etc.) either implicitly or explicitly includes price alongside non-

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<sup>2</sup>Blondal defines a "stage" differently than we do in this paper. We use the term to refer to a decision or set of decisions that depends only on exogenously given parameters and previous decisions. For example, Blondal considers a government agency's solicitation and the vendor offers in response to be a single stage, whereas we treat these as two distinct stages. Using our interpretation, Blondal's model is in fact a five-stage process.





price attributes in the buyer's (auctioneer's) value/utility function.<sup>3</sup> While this approach is appropriate in some contexts, it can generate complications in evaluating alternative defense investments. Unlike private sector decision makers that maximize profits (Revenues minus Costs), the government cannot simply subtract prices (or costs) from non-price attributes and generate an equivalent “profitability” metric to evaluate alternative investment options.

Interestingly, a necessary (but not sufficient) condition for a firm to maximize profits is for it to maximize the value of its output for the costs it incurs (or in the dual: to minimize the costs of producing its output). Interpreting the firm's costs as its budget, this corresponds to maximizing output for a given budget, and is analogous to our proposal for a government activity to maximize its value function (of non-price attributes) for a given affordability (budget) constraint. In fact, the proposal is to promote an approach where government decision makers maximize their value function (over a set of non-price attributes) for a range of budgets they think they might be allocated, but that might not be revealed with certainty within the window of that decision process.

However, historically (and even today) budgets for specific defense products and services were generated by the low cost (or best value) vendor among those responding with price quotes, for the requirements set by the military branches to support warfighters. Given current fiscal deficit projections that promise increasingly tighter budget constraints, it is not likely this approach will survive much longer. Traditional “bottom-up” budgets historically generated by the military services in cooperation with vendors to purchase force requirements, are likely to be subjected to greater top-down budget guidance.<sup>4</sup>

Two widely cited pioneers in defense economics, Hitch and McKean (1967), advocate an approach similar to that proposed in this paper: To determine the “maximum effectiveness for a given budget” and to examine how each alternative fares for several different budget levels.

## The Model

The model consists of three stages, illustrated in Figure 1.

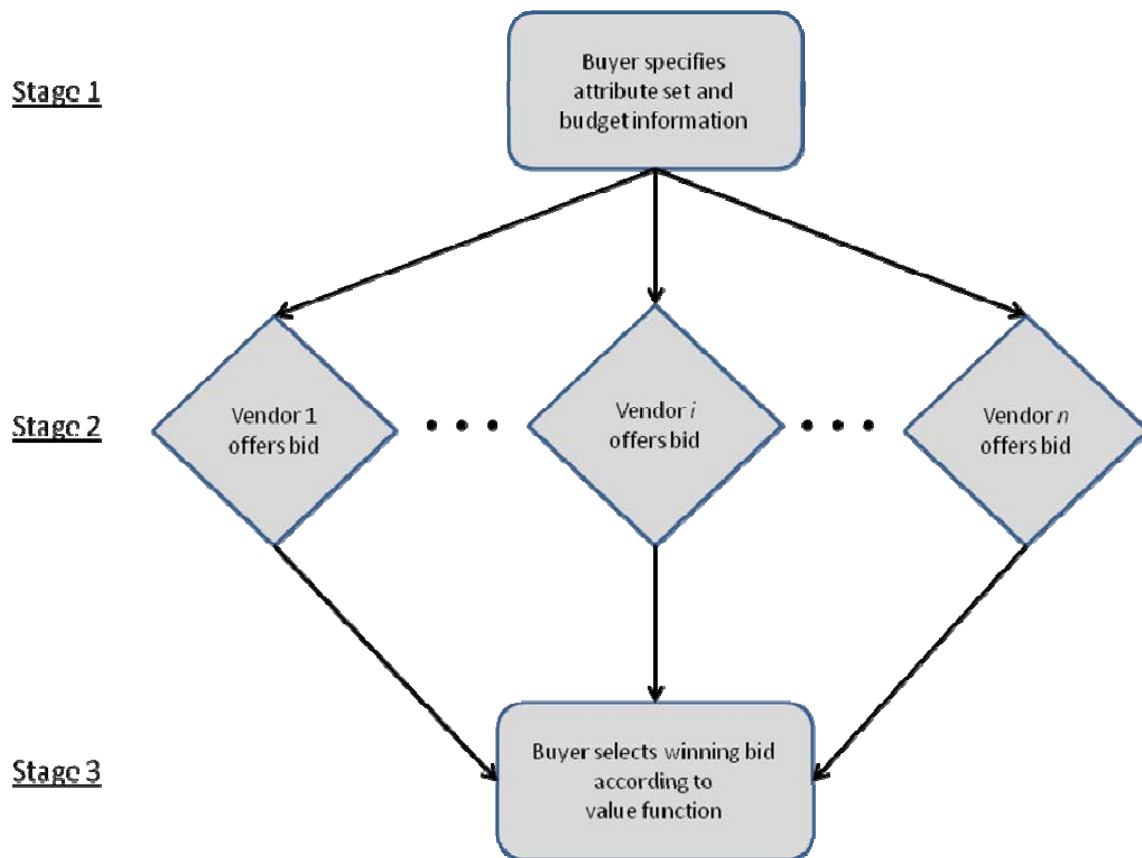
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<sup>3</sup>Note that in defense procurement, value functions generate “measures of effectiveness” (MOEs). The term “MOE” is used in a few different ways. It may describe a single-attribute value function, or a multi-attribute value function which might incorporate the whole objectives hierarchy, or only a portion of it. For a detailed discussion of MOEs, see Sproles (2000).

<sup>4</sup> Some evidence of tighter fiscal guidance appears in the new emphasis on fiscally informed “Planning” that involves more up-front military investment trade-offs, and correspondingly stricter fiscal guidance to the Military Services, in DoD's over-arching “Planning, Programming, Budgeting and Execution System” (PPBES). (See the DoD Comptroller's website.)







### The Three-stage Procurement Model

In the first Stage, the procurement agency (buyer) solicits offers from vendors (sellers), specifying a set of attributes  $A$  and a budget level  $B$ . There are  $n$  vendors, each of whom responds in the second stage with a bid. In this case, a “bid” is simply a set of non-price attribute levels a vendor offers to produce for the budget,  $B$ . We express vendor  $i$ 's bid as  $A_i = [a_{i1}, \dots, a_{im}]$  for  $i = 1, \dots, n$ , where  $a_{ij}$  is the level of attribute  $j$  offered by vendor  $i$ . In the third stage, the buyer's decision is to select a vendor,  $i \in [1, n]$ , and thus a set of attribute levels  $A_i = [a_{i1}, \dots, a_{im}]$ , that maximizes the “measure of effectiveness” (MOE), which we express as the value function  $V(A_i)$ . We assume  $V(A_i)$  is an additive multi-attribute value function, though as we will observe later, our conclusions do not require  $V(A_i)$  to be additive. The use of additive multi-attribute value functions requires that preferential independence be satisfied (Dyer & Sarin, 1979; Kirkwood & Sarin, 1980)<sup>5</sup>. We assume for simplicity that the single-attribute value functions are linear, and that attributes are

<sup>5</sup> See Keeney and Raiffa (1976) and Kirkwood (1997) for further discussion of additive multiattribute value functions. For discussion of the elicitation and use of such preferences in defense applications, see Parnell (2007).



measured on the same scale<sup>6</sup>. Thus, we will refer simply to  $a_{ij}$  rather than using the notation  $v(a_{ij})$ . The buyer's objective is:

$$\max_i V(A_i) = \sum_{j=1}^m w_j a_{ij}, \quad (1)$$

where  $w_j$  is the weight the buyer places on attribute  $j$ . We assume the buyer has an understanding of the range of attribute levels when determining the weights, and that these weights are private information to the buyer. Asker and Cantillon (2007) refer to this as a "secret scoring rule." The final stage of the model is the application of (1) to the set of bids, and the selection of the vendor yielding the highest value.

Given  $A$  and  $B$ , each vendor chooses an attribute bundle which meets the budget constraint revealed by the buyer. A vendor has private information regarding production capabilities and costs, but must somehow form beliefs about the likelihood of a bid being accepted. We facilitate formulation of these beliefs by having each vendor generate a "best guess" at the weights of the buyer's (additive) value function, which we can express as  $W_i = (w_{i1}, \dots, w_{im})$ . We refer to this hypothetical value function as  $Q(A_i)$ . A higher  $Q(A_i)$  indicates a greater probability with which the vendor believes the bid will be accepted. Only the ordinal rankings imposed by this value function are relevant, since vendors in our model will simply choose the attribute bundle (s)he believes has the highest probability of being chosen.

We can express the problem faced by vendor  $i$  as:

$$\begin{aligned} \max_{a_{ij}} Q(A_i) &= \sum_{j=1}^m w_{ij} a_{ij}, \quad j = 1, \dots, m \\ \text{s.t. } TC_i &= \sum_{j=1}^m c_{ij}(a_{ij}) \leq B, \end{aligned} \quad (2)$$

where the total cost  $TC_i$  is an additive function of the costs of firm  $i$  to produce each attribute level. The total costs for a particular vendor of generating its (non-price attribute bundle) offer cannot exceed  $B$ .

The individual attribute cost functions are given by  $c_{ij}(a_{ij})$ , and each one is increasing in  $a_{ij}$ . Because the objective function of (2) is linear, a unique solution exists, provided that  $c_{ij}(a_{ij})$  is strictly convex for  $j = 1, \dots, m$ . This is reasonable, since it simply corresponds to decreasing returns to scale from investment in improving an attribute level.

For purposes of illustration and ease of exposition, the remainder of the study focuses on only two vendors, and two (non-price) attributes measured on the same scale.

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<sup>6</sup>The structure of the single-attribute value functions is not germane to the purpose of this paper. The same results can be obtained without these assumptions, but we believe that some of the subsequent examples will be more illustrative when shown in attribute space rather than value space. Some clarity might be provided by thinking of the attribute levels as performance ratings.



Assuming each vendor has a different technology (production process) to combine the two attributes and faces different attribute cost functions, the Lagrangian function for the vendor's problem is given by:

$$L_i = w_{i1}a_{i1} + w_{i2}a_{i2} - \lambda_i (B - c_{i1}(a_{i1}) - c_{i2}(a_{i2})), \text{ for } i = 1, 2. \quad (3)$$

Since  $\frac{\partial Q(A_i)}{\partial a_{ij}} > 0$  for both attributes, we can assume each vendor will use the maximum available budget  $B$  to produce the attribute bundle proposal. The first order necessary conditions for an optimum are given by:

$$\frac{\partial L_i}{\partial a_{i1}} = w_{i1} + \lambda_i c'_{i1}(a_{i1}) = 0 \quad (4a)$$

$$\frac{\partial L_i}{\partial a_{i2}} = w_{i2} + \lambda_i c'_{i2}(a_{i2}) = 0 \quad (4b)$$

$$\frac{\partial L_i}{\partial \lambda_i} = B - c_{i1}(a_{i1}) - c_{i2}(a_{i2}) = 0, \quad (4c)$$

where 4(c) simply asserts that the entire budget is being used. Solving (4a) and (4b) yields:

$$\frac{w_{i1}}{c'_{i1}(a_{i1})} = \frac{w_{i2}}{c'_{i2}(a_{i2})}, \quad (5)$$

meaning each vendor should choose a bid that uses the entire budget, and for which the two attributes have equal ratios between the (subjective) belief of the weight placed on the attribute by the buyer, and the vendor's private marginal costs<sup>7</sup>. The solicitation for bids results in two vendor offers  $(a_{11}, a_{12})$  and  $(a_{21}, a_{22})$  for the buyer to evaluate. The buyer simply selects the vendor whose bid maximizes  $V$ .

In general,  $w_{ij}$  and  $c_{ij}$ , are likely to differ between vendors. Multi-attribute auctions allow vendors to differentiate themselves in the auction process and to bid on their competitive advantages (Wise and Morrison 2000).

## Multiple Budgets and Expansion Paths

With the preliminary model in place, the next step is for the buyer to more fully explore differences between vendors. Rather than the buyer specifying a budget  $B$ , the buyer now specifies a set of (increasing) possible budgets:  $B_1, \dots, B_k$ . Each vendor will go through the process described in section 2,  $k$  times, and produce a bid satisfying (5) for each of the  $k$  possible budgets. This set of bids from a vendor constitutes an "expansion path." It reveals to the buyer precisely how a vendor's bid will improve as the budget increases.

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<sup>7</sup>Note that (5) has a unique solution for each vendor when the entire budget is being used. Since both cost functions are increasing and strictly convex, as we move along the budget constraint curve, one marginal cost is decreasing and the other is increasing.



For purposes of illustration, it is helpful to consider a particular functional form:

$$c_{ij}(a_{ij}) = \alpha_{ij} e^{\beta_{ij} a_{ij}}, \quad \alpha_{ij}, \beta_{ij} > 0 \text{ for } i = 1, 2, \quad j = 1, 2. \quad (6)$$

Note that the functions described by (6) are strictly increasing and convex. The exponent  $\beta_{ij}$  defines the convexity of each cost function. Although the insights and conclusions that follow do not depend on this particular functional form, it simplifies the analysis to use these cost functions throughout the remainder of the paper.

There are three reasons the expansion paths observed by the buyer might differ between vendors: i) the parameters of their cost functions could differ ( $\alpha_{ij}, \beta_{ij}$ ), ii) their beliefs about the buyer's value function could differ ( $w_{ij}$ ), or iii) both the cost functions and the beliefs could differ.

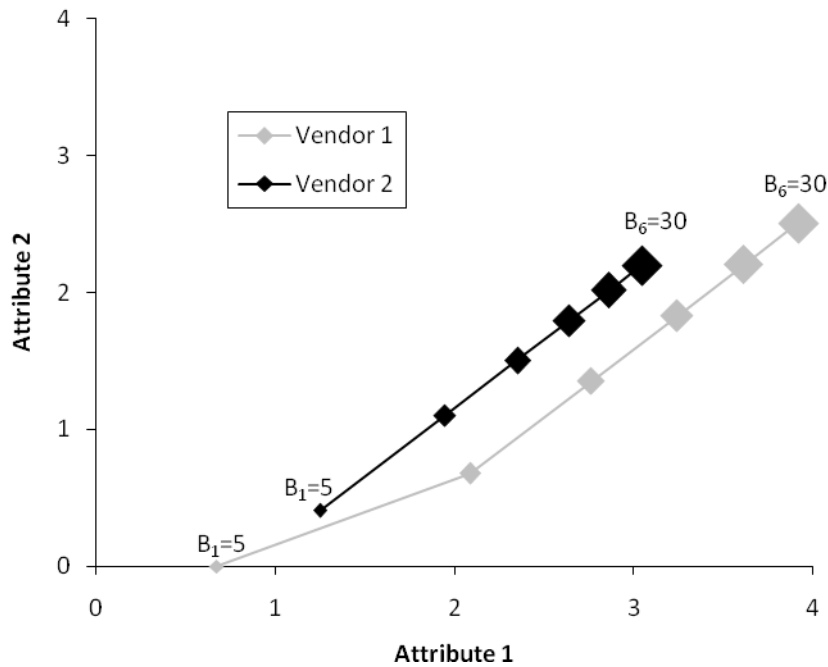
First, consider the case in which both vendors believe the buyer places equal weight on the two attributes, but the vendors differ in their capabilities of producing those attributes. Specifically, suppose:

$$\alpha_{11} = \alpha_{12} = 2.0, \beta_{11} = \beta_{12} = 0.6, \alpha_{21} = \alpha_{22} = 1.0, \beta_{21} = \beta_{22} = 1.0, w_{11} = 0.7, w_{21} = 0.7. \quad (7)$$

Note that (7) reflects symmetry between the two attributes in the sense that neither vendor “specializes” in producing a particular attribute. For simplicity, we use cost functions with these properties throughout this section, and also to emphasize that asymmetry between attributes is not required to realize the benefits of this expansion path approach. Applying (7) results in the expansion paths shown in Figure 2.



## Expansion Paths - Differing Cost Functions



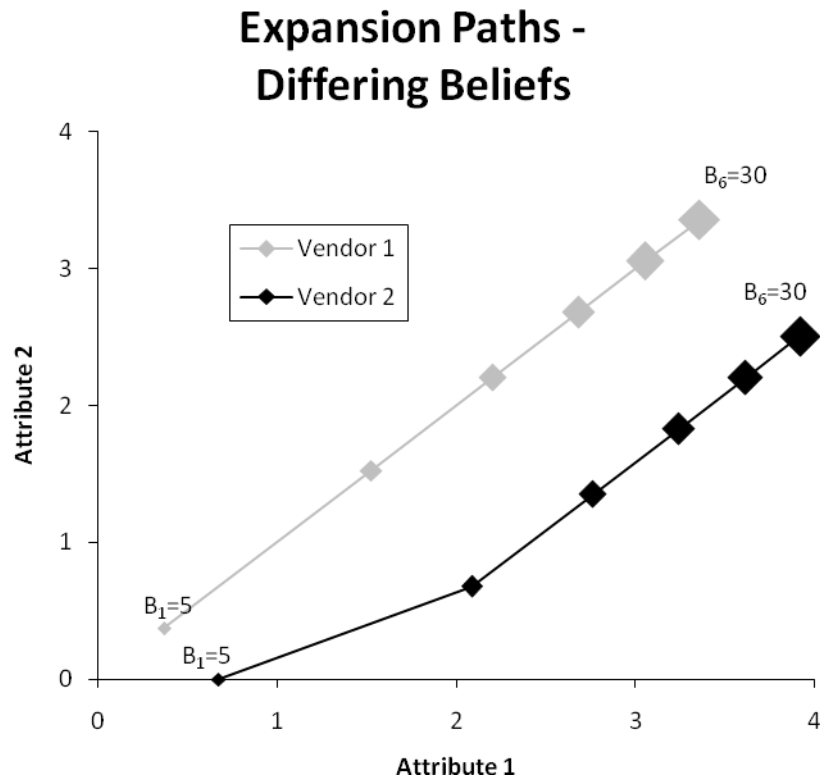
**Figure 1.** Expansion Paths for Two Vendors with Differing Cost Functions as the Budget Increases from 5 to 30 (the Markers of Increasing Size Show Each Vendor's Proposal as the Budget Increases in Increments of 5)

Alternatively, vendors could face the same cost functions, but express different beliefs about the buyer's attribute weights. Specifically, suppose the vendors have the following parameter values:

$$\alpha_{11} = \alpha_{12} = \alpha_{21} = \alpha_{22} = 2.0, \beta_{11} = \beta_{12} = \beta_{21} = \beta_{22} = 0.6, w_{11} = 0.5, w_{21} = 0.7. \quad (8)$$

That is, vendor 2 believes the buyer will place a slightly greater weight on attribute 1, while vendor 1 believes the weights on attribute 1 and attribute 2 will be equal. This results in the expansion paths shown in Figure 3.





**Figure 2.** Expansion Paths for Two Vendors with Differing Beliefs on Attribute Weights as the Budget Increases from 5 to 30 (the Markers of Increasing Size Show Each Vendor's Proposal as the Budget Increases in Increments of 5)

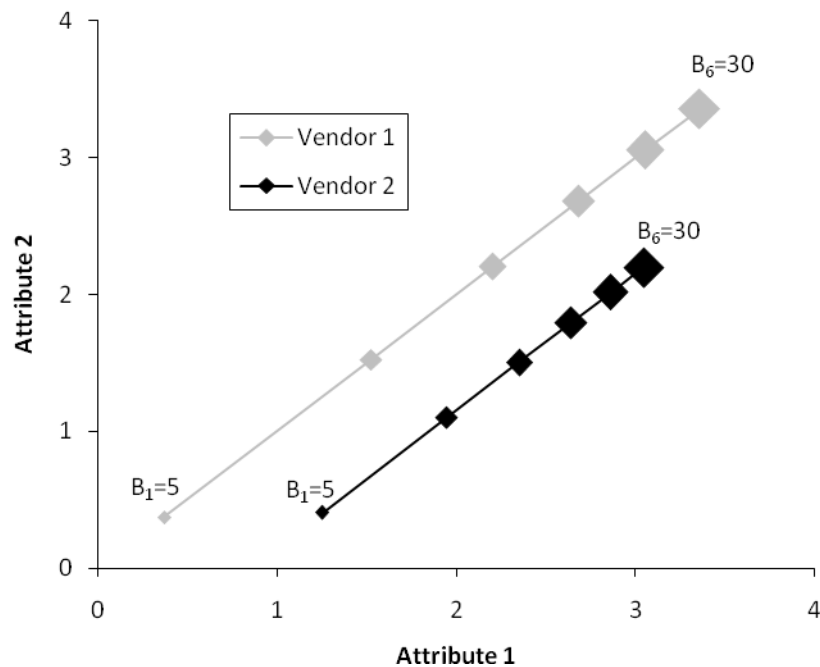
While (7) and (8) are interesting special cases, it is also possible the two vendors will differ in both their costs and their beliefs. Consider two vendors with parameter values:

$$\alpha_{11} = \alpha_{12} = 2.0, \beta_{11} = \beta_{12} = 0.6, \alpha_{21} = \alpha_{22} = 1.0, \beta_{21} = \beta_{22} = 1.0, w_{11} = 0.5, w_{21} = 0.7. \quad (9)$$

In this case, we observe an interesting dynamic, as shown in Figure 4.



## Expansion Paths - Differing Beliefs and Cost Functions



**Figure 3. Expansion Paths for Two Vendors with Differing Costs and Beliefs on Attribute Weights (the Markers of Increasing Size Show Each Vendor's Proposal as the Budget Increases in Increments of 5)**

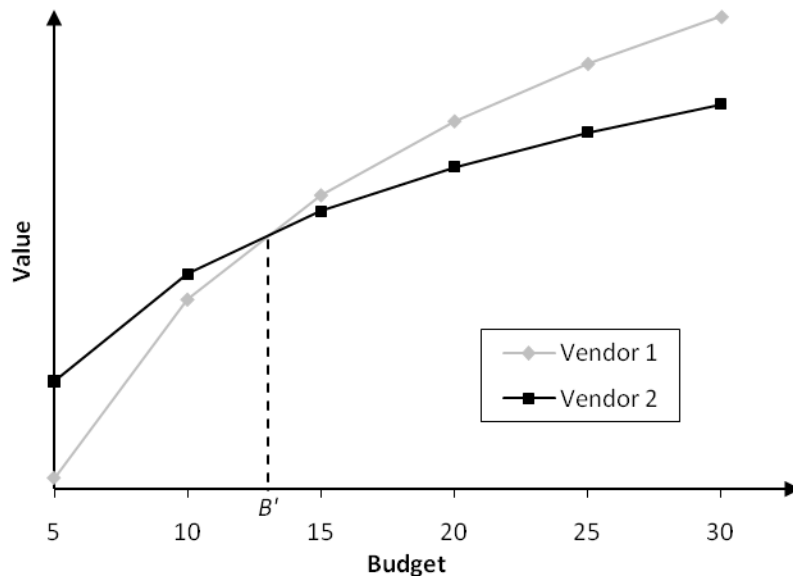
For a high budget (e.g., 20), vendor 1 dominates vendor 2. Regardless of the buyer's preferences (provided value is monotonically increasing in each attribute), (s)he will select vendor 1. In a static comparison that assumes a fixed budget of 20, vendor 2 would be eliminated from further consideration. However, if the buyer must proceed knowing that a budget cut is possible, a dominated alternative may in fact become the preferred one. The reverse phenomenon can also occur. Notice in Figure 4 that vendor 2 dominates vendor 1 at a budget level of 5. A static comparison assuming a fixed budget of 5 would eliminate vendor 1 from further consideration.

To more clearly illustrate this phenomenon, we first assign attribute weights to the buyer's value function. Let the buyer assign a weight of 0.7 to attribute 1, and 0.3 to attribute 2. Instead of operating as before in attribute space, we now plot the two vendors' bids illustrated in Figure 4 as curves in "budget-value" space:





## Value by Budget Level



**Figure 4. Value Provided by Each Vendor's Bid for Various Budget Levels**

It is clear from Figure 5 that vendor 2 dominates the competition for any positive budget below the switch-point,  $B < B'$ , while vendor 1 dominates for any budget above the switch-point,  $B > B'$ . This suggests rethinking the typical definition of dominance in the literature, a concept routinely used in classroom illustrations and real-world applications to eliminate vendors that refers to points (not functions) in cost-effectiveness space.

In fact, viewing alternative vendors as functions in budget-value space reveals that the traditional definition of dominance can be misleading. For example, consider offers from vendor 1 and vendor 2 based on a very optimistic budget above  $B'$ . The traditional technique that focuses on points and not functions would likely eliminate vendor 2. Yet it is clear from Figure 5 that eliminating vendor 2 prematurely could lead to a less desirable outcome if the budget turned out to be wildly optimistic and the real budget was actually somewhere in the range of  $0 < B < B'$ .

This phenomenon can occur whenever any two vendors' expansion paths are shaped differently, and there is nothing unique about the particular functions chosen in our example; they were only selected for ease of exposition. Moreover, the same result can easily occur in the case of non-additive forms of the buyer's value function, and any non-linear interactions between attributes is likely to further magnify the effect<sup>8</sup>. Our conclusion is that this is a basic result that can arise in a wide variety of defense acquisition decision environments. Addressing this issue explicitly with this simple new approach could greatly benefit both our troops and taxpayers. Given the growing US federal deficit, future budget

<sup>8</sup>For example, consider a multiplicative value function for the buyer, and suppose that one vendor has to incur a large cost to provide anything above the minimum level for one particular attribute. This vendor will offer bids of little to no value for low budgets, but depending on cost functions and beliefs, may offer very attractive bids for higher budgets.



challenges may make it imperative for our government, and in particular the Department of Defense, to adopt an approach similar to the one proposed in this study.

## Conclusion

We have described a simple three-stage multi-attribute procurement process for defense acquisitions. It allows the buyer to incorporate preferences over multiple attributes, and it allows each vendor to offer their best possible bid based on the budget provided, and the vendor's private cost structure and beliefs. Unlike most current methods, our model applies the spirit of CAIV; we do not include costs or any related price attributes in the buyer's value function. Instead, cost enters the model as part of a budget constraint.

The basic model is easily extended to allow vendors to submit bids for multiple potential budget levels. This leads to the generation of expansion paths for each vendor, which illustrates to the buyer precisely how a particular vendor's bid will improve under more optimistic budgets or slip under progressive budget cuts.

Interestingly, it can easily turn out that a vendor whose bid is "dominated" at an optimistic budget level is actually the most desirable choice at a more realistic (pessimistic) budget level. As a consequence it is vital for procurement agencies to reset their vendor evaluations, and to begin viewing each alternative (vendor) as a curve in budget-value space, rather than as a single cost-effectiveness point. Given future budget realities, this expanded view will prevent a vendor from being prematurely eliminated from consideration when budgets are likely to change over time.

The dual fundamental insights of this study are that public procurement decisions can be improved if: i) interval estimates (ranges) of future budgets (and corresponding probability distributions) are forecasted, and ii) information from vendors is solicited that allows procurement alternatives to be defined as a function of value (non-price attributes) over a range of possible budgets, rather than as a single point in budget-value (cost-effectiveness) space. The key implication is that different vendor selection decisions are likely to occur under more realistic budget scenarios, and that this can benefit both troops and taxpayers.

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- Acquiring Combat Capability via Public-Private Partnerships (PPPs)
- BCA: Contractor vs. Organic Growth
- Defense Industry Consolidation
- EU-US Defense Industrial Relationships
- Knowledge Value Added (KVA) + Real Options (RO) Applied to Shipyard Planning Processes
- Managing the Services Supply Chain
- MOSA Contracting Implications
- Portfolio Optimization via KVA + RO
- Private Military Sector
- Software Requirements for OA
- Spiral Development
- Strategy for Defense Acquisition Research
- The Software, Hardware Asset Reuse Enterprise (SHARE) repository

### **Contract Management**

- Commodity Sourcing Strategies
- Contracting Government Procurement Functions
- Contractors in 21<sup>st</sup>-century Combat Zone
- Joint Contingency Contracting
- Model for Optimizing Contingency Contracting, Planning and Execution
- Navy Contract Writing Guide
- Past Performance in Source Selection
- Strategic Contingency Contracting
- Transforming DoD Contract Closeout
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### **Financial Management**

- Acquisitions via Leasing: MPS case
- Budget Scoring
- Budgeting for Capabilities-based Planning



- Capital Budgeting for the DoD
- Energy Saving Contracts/DoD Mobile Assets
- Financing DoD Budget via PPPs
- Lessons from Private Sector Capital Budgeting for DoD Acquisition Budgeting Reform
- PPPs and Government Financing
- ROI of Information Warfare Systems
- Special Termination Liability in MDAPs
- Strategic Sourcing
- Transaction Cost Economics (TCE) to Improve Cost Estimates

## **Human Resources**

- Indefinite Reenlistment
- Individual Augmentation
- Learning Management Systems
- Moral Conduct Waivers and First-term Attrition
- Retention
- The Navy's Selective Reenlistment Bonus (SRB) Management System
- Tuition Assistance

## **Logistics Management**

- Analysis of LAV Depot Maintenance
- Army LOG MOD
- ASDS Product Support Analysis
- Cold-chain Logistics
- Contractors Supporting Military Operations
- Diffusion/Variability on Vendor Performance Evaluation
- Evolutionary Acquisition
- Lean Six Sigma to Reduce Costs and Improve Readiness
- Naval Aviation Maintenance and Process Improvement (2)
- Optimizing CIWS Lifecycle Support (LCS)
- Outsourcing the Pearl Harbor MK-48 Intermediate Maintenance Activity
- Pallet Management System
- PBL (4)
- Privatization-NOSL/NAWCI
- RFID (6)



- Risk Analysis for Performance-based Logistics
- R-TOC AEGIS Microwave Power Tubes
- Sense-and-Respond Logistics Network
- Strategic Sourcing

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- Business Process Reengineering (BPR) for LCS Mission Module Acquisition
- Collaborative IT Tools Leveraging Competence
- Contractor vs. Organic Support
- Knowledge, Responsibilities and Decision Rights in MDAPs
- KVA Applied to AEGIS and SSDS
- Managing the Service Supply Chain
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## **Military Cost-Benefit Analysis: A Multi-Attribute Three-Stage Procurement Model**

Francois Melese, Jay Simon (presenter)

Defense Resources Management Institute  
Naval Postgraduate School

# Introduction

- Large & rising federal debt, shrinking discretionary budget
  - Budget uncertainty!
- Defense procurement typically requires vendors to submit bids which include
  - Price
  - Performance attributes
- Problem: Optimal vendor choice may change with changes in the budget!



# Budget Constraint

- Based on an “Economic Evaluation of Alternatives” (EEoA)\* approach:
  - The procurement agency buyer reveals desired attributes and the budget for the program
  - Vendor offers (bids) consist of product proposals to produce a set of performance attributes for a given budget authority
  - The procurement agency buyer selects a vendor according to the buyer’s (“secret”) weighting of the attributes (i.e. a multi-attribute value function)

\* See pp. 25-28 in Melese, F. “The Economic Evaluation of Alternatives,” Proceedings of the 6<sup>th</sup> Annual Acquisition Research Symposium: Defense Acquisition in Transition, Vol 1.

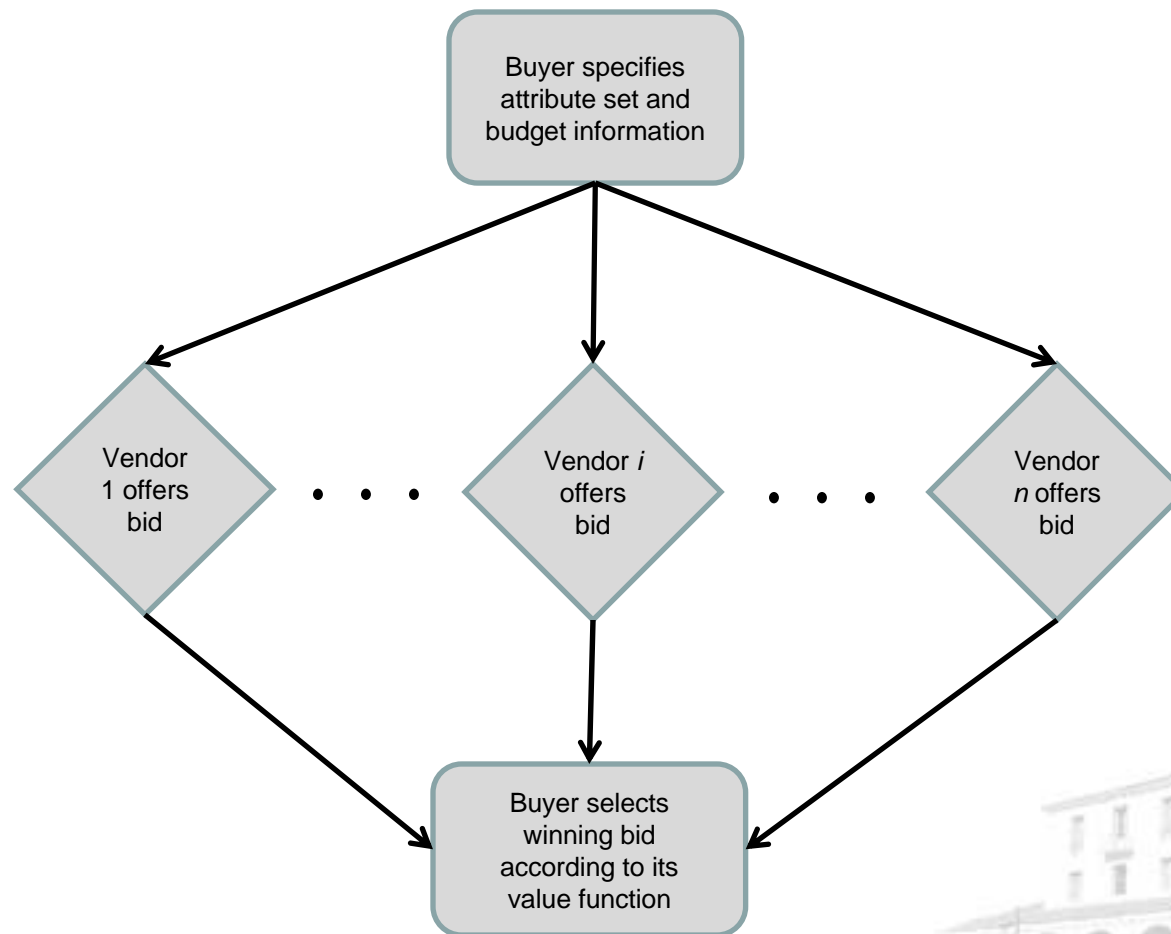


# Model Structure

Stage 1

Stage 2

Stage 3



# Model

- $n$  vendors
- Set of attributes  $A = (1, \dots, m)$
- Vendor  $i$ 's offer is  $A_i = [a_{i1}, \dots, a_{im}]$
- Buyer's "secret" value function (MOE) is  $V(A_i)$
- Budget level is  $B$
- Buyer makes selection decision according to:

$$\max_i V(A_i) = \sum_{j=1}^m w_j a_{ij}$$





# Vendor's Decision Problem

- Private information on production capabilities and costs:
  - Captured by cost functions  $c_{ij}(a_{ij})$
- Does not know  $V$ , but forms beliefs about the buyer's preferences
- “Best guess”  $\gamma_i = (\gamma_{i1}, \dots, \gamma_{im})$
- Results in a hypothetical value function to maximize:  $Q(A_i) = \sum_{j=1}^m \gamma_{ij} a_{ij}$



# Vendor's Decision Problem

- Vendor  $i$ 's problem can be expressed as:

$$\begin{aligned} \max_{a_{ij}} \quad & Q(A_i) = \sum_{j=1}^m \gamma_{ij} a_{ij} \\ \text{s.t.} \quad & TC_i = \sum_{j=1}^m c_{ij} (a_{ij}) \leq B \end{aligned}$$



# Simplified Approach

- For the sake of clarity, the remainder of the analysis will assume:

**Two attributes**

**Two vendors**



# Solution to Vendor's Problem

- A vendor's best offer (bid) will be a combination of attribute levels that uses the entire budget, and satisfies the condition:

$$\frac{\gamma_{i1}}{c'_{i1}(a_{i1})} = \frac{\gamma_{i2}}{c'_{i2}(a_{i2})}$$

- The buyer then chooses the vendor that maximizes its military effectiveness value,  $V$ , for the planned budget,  $B$



# Budget Uncertainty

- Now, instead of  $B$ , consider a range of possible budgets:  $B_1, \dots, B_k$
- Each vendor submits an offer (bid) for each of the  $k$  possible budgets
- This set of offers from a vendor constitutes an “expansion path”



# Examples

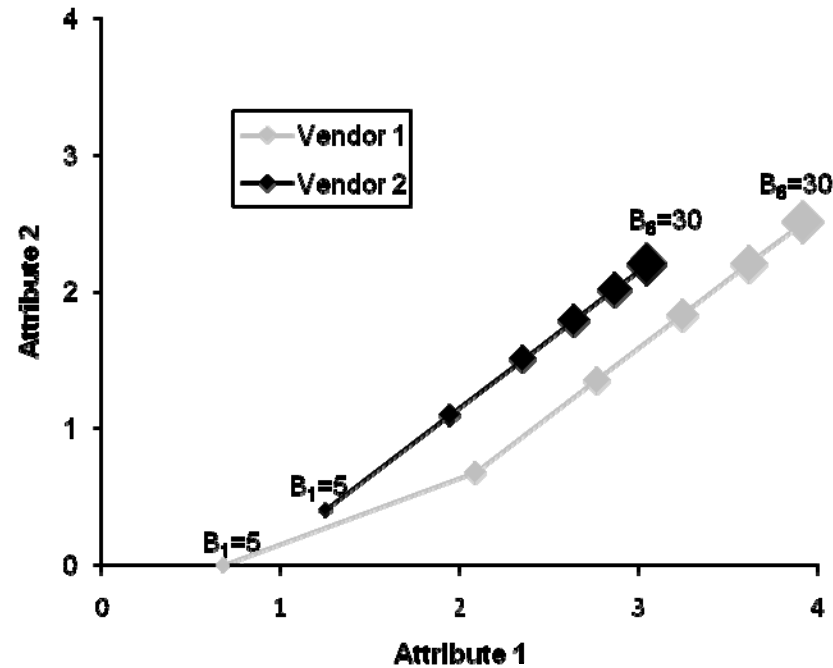
- Let the vendors have cost functions of the form:

$$c_{ij}(a_{ij}) = \alpha_{ij} e^{\beta_{ij} a_{ij}}, \text{ where } \alpha_{ij}, \beta_{ij} > 0$$

- $B_1=5, B_2=10, B_3=15, B_4=20, B_5=25, B_6=30$
- We will examine several cases where the vendors differ in their cost functions and/or beliefs about the weight the buyer places on the attributes



## Expansion Paths - Differing Cost Functions

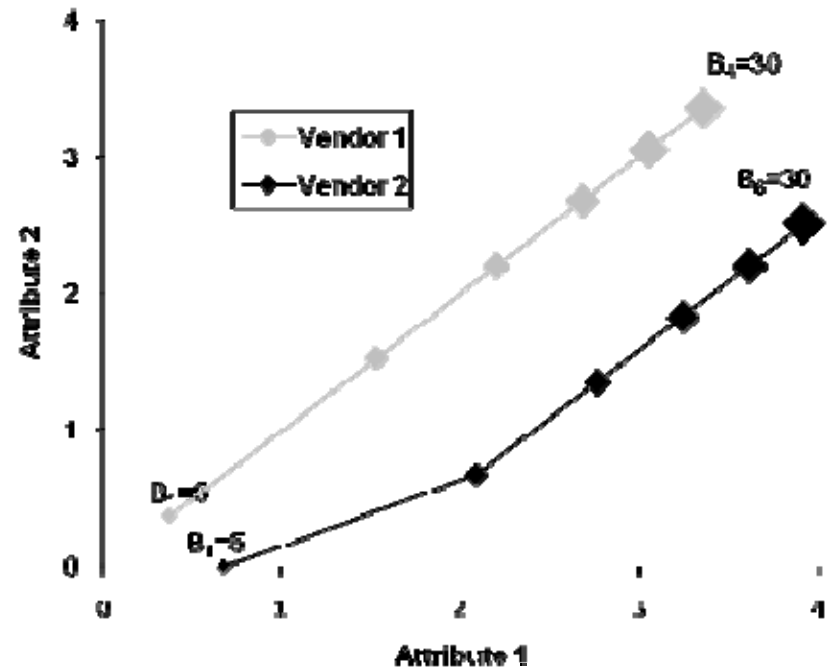


$$\alpha_{11} = \alpha_{12} = 2.0, \beta_{11} = \beta_{12} = 0.6, \alpha_{21} = \alpha_{22} = 1.0, \beta_{21} = \beta_{22} = 1.0, \gamma_{11} = 0.7, \gamma_{21} = 0.7$$





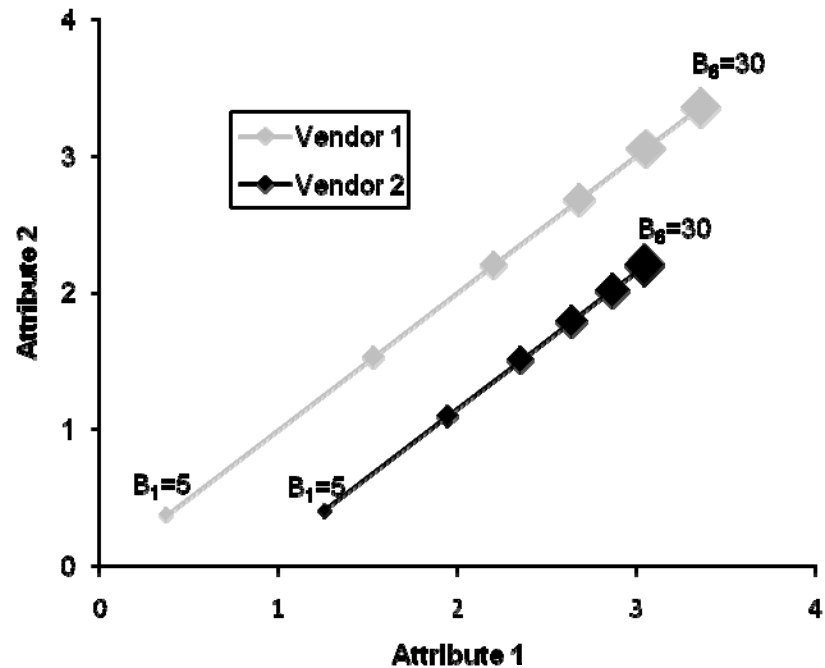
## Expansion Paths - Differing Beliefs ( $\gamma$ )



$$\alpha_{11} = \alpha_{12} = \alpha_{21} = \alpha_{22} = 2.0, \beta_{11} = \beta_{12} = \beta_{21} = \beta_{22} = 0.6, \gamma_{11} = 0.5, \gamma_{21} = 0.7$$



## Expansion Paths - Differing Beliefs and Cost Functions



$$\alpha_{11} = \alpha_{12} = 2.0, \beta_{11} = \beta_{12} = 0.6, \alpha_{21} = \alpha_{22} = 1.0, \beta_{21} = \beta_{22} = 1.0, \gamma_{11} = 0.5, \gamma_{21} = 0.7$$

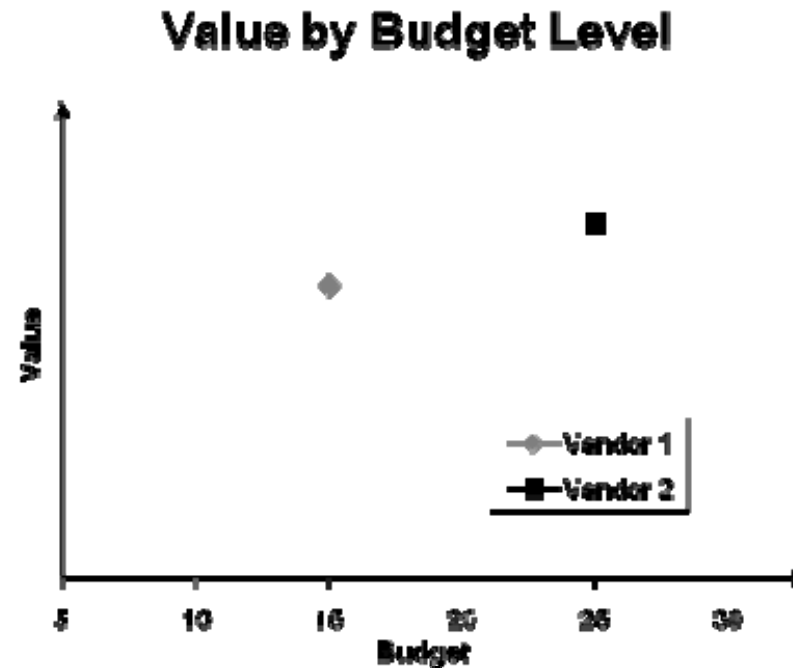


# Switch to Budget-Value Space

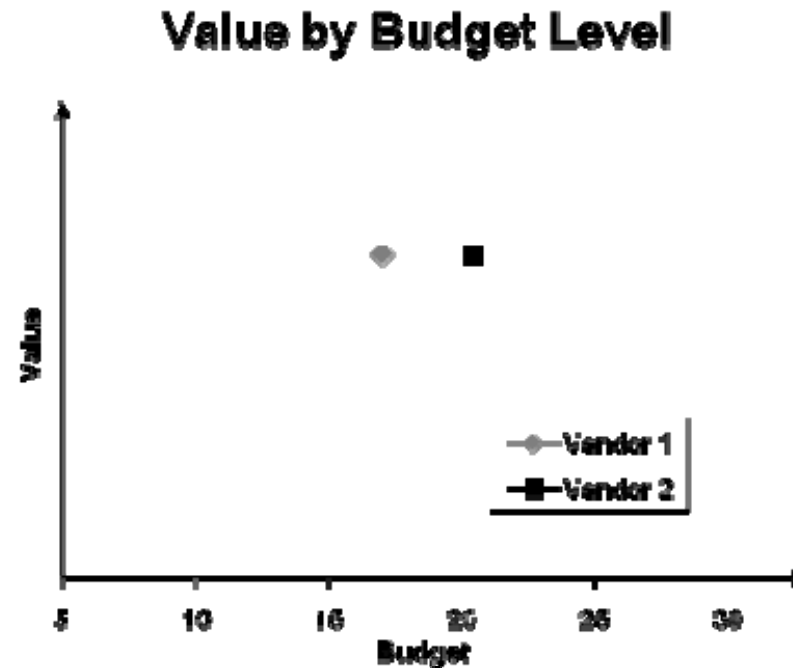
- What is the value to the buyer (procurement agency; warfighter) provided by each vendor for a specific budget authority?
- What is the value to the buyer provided by each vendor over all possible budget levels?
- Assume the two vendors have the properties from the last graph, and that the buyer places a weight of 0.7 on attribute 1



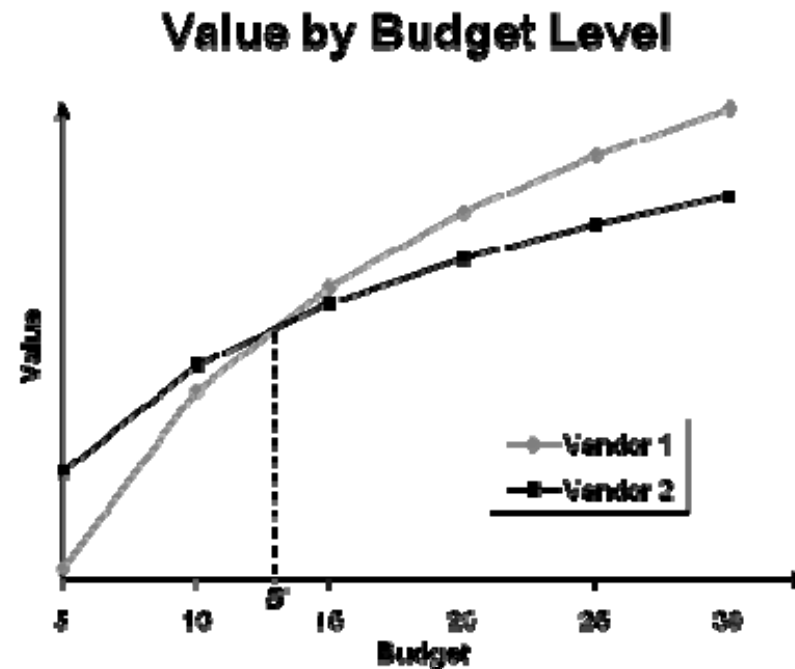
# Traditional Price & Performance Bid



# Air Tanker Costs for Given Level of Effectiveness (Boeing vs. EADS?)



# Vendor Bids: Performance Offers over a Range of Budgets



# Next Steps

- Model the budget uncertainty with a probability distribution, and determine the expected utility provided by each vendor
- Include uncertainty in vendor performance (quantity, quality, schedule) promises
  - May be framed as either cost uncertainty or performance uncertainty or both (depends on the particular contract structure)

